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Voltage Scheduling Droop Control for State-of-Charge Balance of Distributed Energy Storage in DC Microgrids

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***Abstract*— Due to higher power quality, lower conversion loss, and more DC loads, there has been an increasing awareness on DC microgrid. Previous emphasis has been on equal power sharing among different units in the DC microgrid, while overlooking the coordination of the energy storage units to maintain the State-of-Charge balance. In this paper, a new droop method based on voltage scheduling for State-of-Charge balance is proposed to keep the SoC balance for the energy storage units. The proposed method has the advantage of avoiding the stability problem existed in traditional methods based on droop gain scheduling. Simulation experiment is taken in Matlab on a DC microgrid with two distributed energy storage units. The simulation results show that the proposed method has successfully achieved SoC balance during the load changes while maintaining the DC bus voltage within the allowable range.**

***Keywords:* Voltage Scheduling, State-of-Charge Balance, Energy Storage, DC Microgrids.**

I. Introduction

Microgrid is defined as a local grid that is comprised of distributed generation, energy storage systems (ESS) and local loads. According to the source type, microgrids can be divided into AC microgrids and DC microgrids. Without inherent problems related to AC microgrids (such as the need for synchronization of the distributed generators, the inrush currents due to transformers, reactive-power flow, harmonic currents, and three-phase unbalances) and with more and more modern DC components (such as photovoltaic panels, batteries, fuel cells, LEDs, and electronic loads), as well as with less conversion loss, DC microgrid is gaining increasing interests [1]-[5]. By now, the application of DC microgrids can be found in data centers, telecom systems, and some residential and commercial buildings, and there is a trend toward adopting more DC distribution networks.

In the application of the DC microgrid, the energy storage system, consisted of energy storage units and relative controllers, is an indispensable part for ensuring power quality of the DC microgrid. For one thing, the availability of the renewable energy source is intermittent in nature, and thus the energy storage system is needed as buffers to fill either the shortage of the power generated by renewable energy resource or that consumed by the load. For another, to add redundancy to the system, more than one energy storage unit is needed, and thus the coordination control of these energy storage units is required by the energy storage system.

In the previous researches, emphasis was only focused on the target of equal load sharing, using droop control [6] - [8]. Since droop control can achieve the specific power sharing without communication, droop control and its variants are most commonly used in microgrids than others as in [9]-[11]. However, when more than one energy storage unit is participating in the microgrid, some energy storage units would be exposed to the risk of deep-discharge or overcharge if there is no control to ensure the stored energy balance. Even the Battery Management System (BMS) is to balance the SoC and the output voltage of each cell in the battery string, it cannot coordinate the several energy storage units [12]-[14]. It is desirable that, during discharging, the storage unit with higher SoC will provide more power than the others, and accordingly, during charging, the one with lower SoC will absorb more than the others. Therefore, some of the recent works take state-of-charge (SoC) into consideration by gain-scheduling droop method to balance the output power in each battery [1], [3], [15]-[17]. Although modifying the droop coefficients can successfully make the SoC balanced, it overlooks the fact that according to the state-space analysis the droop coefficients has larger impact on the stability of the system, especially when the system contains more converters.

In this paper, instead of modifying virtual impedance, a new droop method based on voltage scheduling is proposed. The main aim of the control is to keep State-of-Charge of different energy storage units balanced with variable load and generation. By modifying voltage reference, it can avoid the stability problem existed in traditional methods when it realizes the State-of-Charge balance by gain scheduling.

The paper is organized as follows. In Section II, we first adopt state-space analysis to compare the impact of R_d and V_{ref} respectively on system stability, to illustrate that virtual impedance R_d has larger impacts to the system stability. Then in Section III, a new method based on voltage scheduling for State-of-Charge balance is proposed, which has better stability characteristics. The simulation results of a DC microgrid with two energy storage units are presented in Section IV to test the proposed method. Finally, Section V concludes the paper.

II. Comparison of Impacts on Stability of Control Variables

A. State-space model of the system

Usually, the energy storage unit utilize a BUCK DC/DC converter to control its charging and discharging. Although many control methods have been proposed [9]-[11], droop control is the most commonly used method to control these paralleled DC/DC converters.

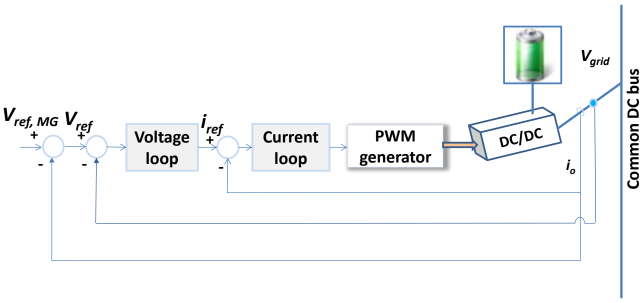


Fig. 1. ESS connected to the common DC bus

Connection of voltage-droop controlled energy storage unit with the corresponding control circuit to the common DC bus is shown in Fig. 1.

If a lossless and non-isolated BUCK DC/DC converter is considered, system of Fig. 1 can be modelled with coupled differential equations:

$$\dot{x}_1 = -I_v R_d x_3 - I_v V_c + I_v V_{ref,MG} \tag{1}$$

$$\dot{x}_2 = I_c x_1 - I_c (R_d P_v + 1) x_3 - I_c P_v V_c + I_c P_v V_{ref,MG} \tag{2}$$

$$\dot{x}_3 = \frac{P_c V_{in}}{L} x_1 + \frac{V_{in}}{L} x_2 - \frac{P_c V_{in} (R_d P_v + 1)}{L} x_3 - \frac{V_{in} P_v P_c + 1}{L} V_c + \frac{V_{in} P_v P_c + 1}{L} V_{ref,MG} \tag{3}$$

$$\dot{v}_c = \frac{1}{C} x_3 - \frac{1}{R_L C} V_c \tag{4}$$

x_1 denotes the output of the integrator of the voltage loop, x_2 denotes the output of the integrator of the current loop, x_3 denotes the filter inductor current, v_c denotes the filter capacitor voltage (equal to the common bus voltage if unit is directly connected). P_v, P_c, P_{sc}, I_v, I_c and I_{sc} are the control parameters of voltage and current loop and voltage secondary control PI controllers, L and C are inductance and capacitance of the converter output filter, R_L is the equivalent resistance of the connected load, V_{in} is the source voltage and $V_{ref,MG}$ is the reference voltage for secondary voltage control.

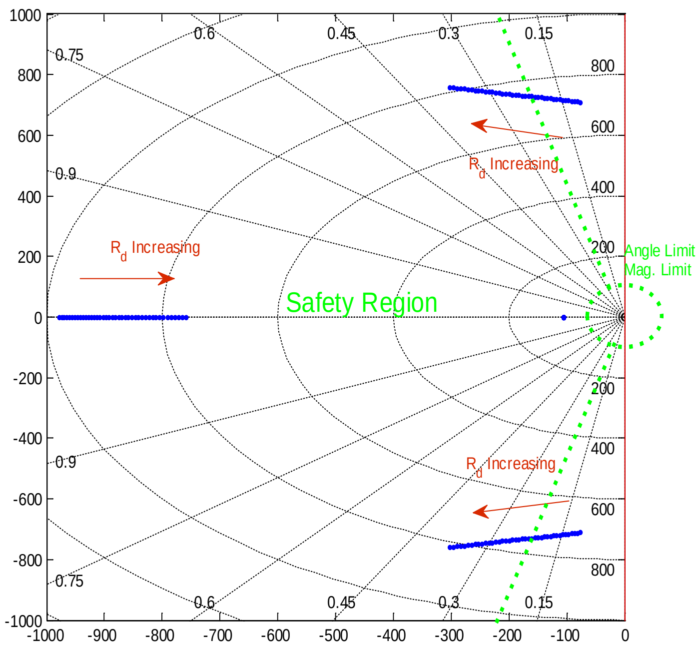
B. R_d and V_{ref} impact analysis comparison on system stability

The parameters in Table I are fixed for the following two cases. The denotations of the parameters in Table I are the same with those described in section A. To analyse the impact of R_d on system stability, the R_d is changed from 0.1~0.5Ω while the V_{ref} is fixed as 48V, and the shifting route of eigenvalues is shown in Fig. 2 (a) (see blue tracks). Similarly, the V_{ref} is changed from 46~50V to see the impact of it while the R_d is fixed as 0.1 Ω, and the diagram is showed in Fig. 2 (b).

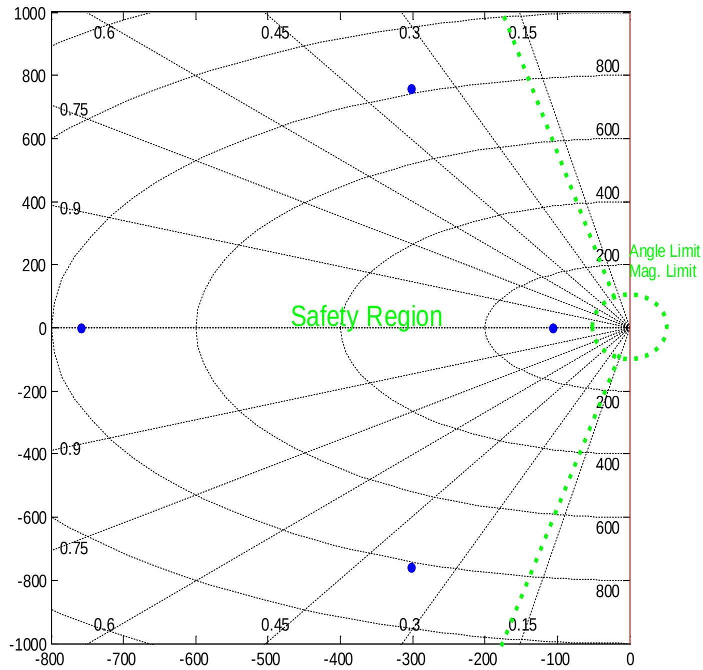
TABLE I
PARAMETERS OF A VOLTAGE-DROOP CONTROLLED ENERGY STORAGE

Fixed parameters	
L	1.8e-3 H
C	2.2e-3 F
R_L	3Ω
P_c	1
I_c	97
P_v	0.5
I_v	993
P_{sc}	0.02
I_{sc}	70

From Fig. 2 (b), it can be seen that when changing V_{ref}, from 46~50V all the eigenvalues of the system are within the safety region, while changing R_d, the eigenvalues of the system will lie out of the safety region when the R_d is too small which is showed in Fig. 2 (a). We can say from this analysis results that modifying V_{ref} is preferable than R_d in term of the stability.



(a)Impact of R_d on system stability



(b) Impact of V_{ref} on system stability

Fig. 2. Impact of R_d and V_{ref} on system stability

III. Proposed Droop Control by Modifying V_{REF}

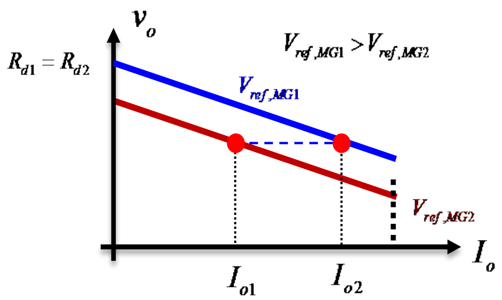
To avoid the stability problem existed in traditional methods based on gain scheduling when achieving the State-of-Charge, a new droop method based on voltage scheduling is proposed.

A. Traditional droop control for ESS without SoC balancing

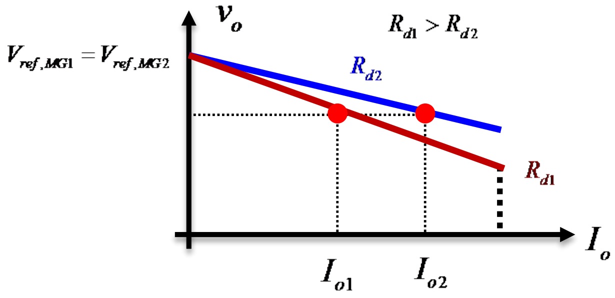
Before describing the proposed method, the traditional method is reviewed. Using the traditional droop control without considering SoC balancing the static output characteristic of the system can be described as:

$$v_o = V_{ref,MG} - R_d i_o \tag{5}$$

The relationship of static output characteristic with R_d and $V_{ref,MG}$ is illustrated in the following diagrams.



(a) R_d is fixed



(b) $V_{ref,MG}$ if fixed

Fig. 3. Relationship of static output characteristic with R_d and $V_{ref,MG}$

Accoding to Fig. 3, either chaning virtual imepdcance or the voltage reference, the power sharing will be changed. Therefore by modifying them, we can make energy storage units deeper charged to provide more power, and energy storage units deeper discharged to provide less power. As discribed in Section II, it is desirable to modify $V_{ref,MG}$ instead of R_d .

B. Droop control for ESS with SoC balancing by voltage scheduling

Fig.4 is a DC microgrid with two energy storage units, and the proposed method is described based on this system. Before giving the control strategy to achieve SoC balance, the SoC calculation method is firstly explained. The SoC estimation arithmetic adopted is coulomb counting, which is expressed as below.

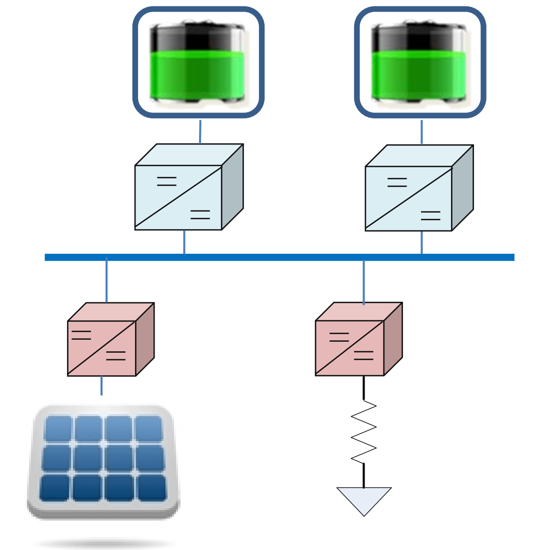


Fig.4 Structure of the test DC microgrid

$$SoC_1 = SoC_1^* - \frac{1}{C_e}\int i_{b1} dt \tag{6}$$

$$SoC_2 = SoC_2^* - \frac{1}{C_e}\int i_{b2} dt \tag{7}$$

where i_{b1} and i_{b2} are the output currents of each battery, SoC_1^* and SoC_2^* are the initial values of SoC, and C_e is the battery capacity.

If the power loss in the converter can be omitted and the output voltages of the batteries are the same, there are following equations,

$$P_1 = P_{in1} = V_{in} i_{b1} \quad (8)$$

$$P_2 = P_{in2} = V_{in} i_{b2} \quad (9)$$

where V_{in} is the input voltage of the converter, P_1 and P_2 are the output power of each converter, and P_{in1} and P_{in2} are the input power of each converter.

So combining the (6) ~ (9), the SoC calculation can be written as

$$SoC_1 = SoC_1^* - \frac{1}{C_e V_{in}} \int P_1 dt \quad (10)$$

$$SoC_2 = SoC_2^* - \frac{1}{C_e V_{in}} \int P_2 dt \quad (11)$$

The control diagram for voltage scheduling of the proposed method is showed in Fig. 5, other control remains the same as showed in Fig. 1.

where α is a proportional coefficient and X_k is defined as below.

$$X_k = \frac{SoC_k}{\frac{1}{n-1} \times (\sum_{i=1}^{n} SoC_i - SoC_k)} \quad (12)$$

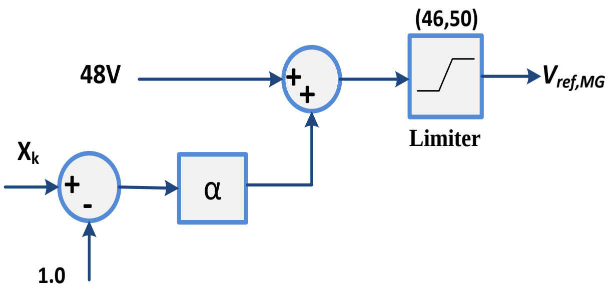


Fig. 5. Control diagram for Voltage scheduling

With this scheduling mechanism, the power sharing of the energy storage unit can be controlled accordingly with the change of the State-of-Charge of each energy storage unit.

IV. Simulation

To validate the proposed control strategy, the simulation of a test DC microgrid is set up in Matlab using SimpowerSystem, and the structure of the system is showed in Fig. 4. The test DC microgrid contains two energy storage units, constant power load and renewable energy source. The parameters of each energy storage unit are the same with that listed in Table I.

Initially, these two energy storage units have the initial SoC as 90% and 60% respectively. At the beginning, the power produced by renewable energy source is less than that consumed by the load; the energy storage is discharging at the rate of 480W to fill the power shortage of renewable enrgy source. At the time of 8 s, the renewable energy source starts to produce more power than needed; the ESS begins to charge at the rate of 50W, to store the extra energy produced by the renewable energy resource.

The curve in Fig. 6. shows the value of voltage reference in the droop control in the converters connected with energy storage units. Contract with traditional droop control strategy, the voltage reference is not a constant value but varied all the time according the proposed control strategy which tries to balance the SoC of each unit.

The curves of SoC1, SoC2 and their difference, are showed in Fig. 7. As can been seen, the different initial SoC of the two energy storage units converge to each other as simulation processes with the difference of them becomes smaller and smaller. In the end, the difference of SoC of these two energy storage units reaches zero, i.e., the SoC of the system reaches a balance.

The curve of output current of the each energy storage units, and DC bus voltage is showed in Fig. 8. As can be seen, at the same time, the bus voltage remains within the permitted range. The scheduling of the power can also be showed from the output current of the ESS. Energy storage unit with lower SoC discharges less and charges more, while one with higher SoC discharges more and charges less.

V. Conclusion

In this paper, a new droop method based on voltage scheduling for State-of-Charge balance is proposed to avoid the stability problem existed in traditional methods based on droop gain scheduling. Simulation experiment is taken in Matlab on a DC microgrid with two distributed energy storage units. The simulation results show that the proposed method has successfully achieved SoC balance during the load changes while maintaining the DC bus voltage within the permitted range.

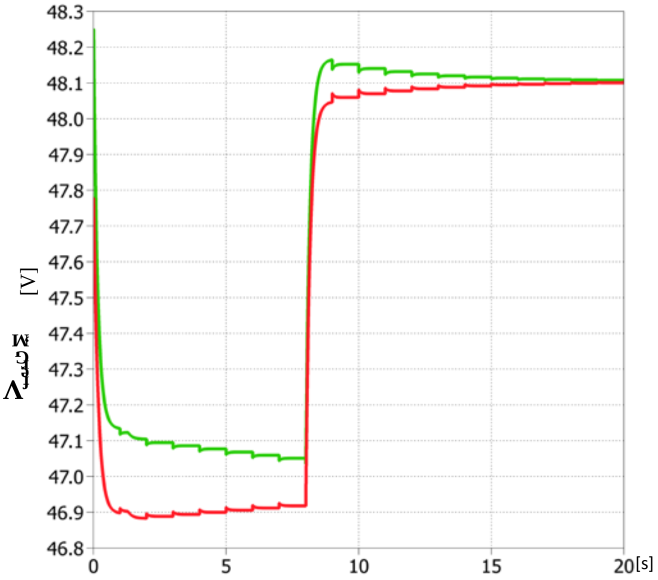


Fig. 6. Voltage reference in the droop Vref,MG

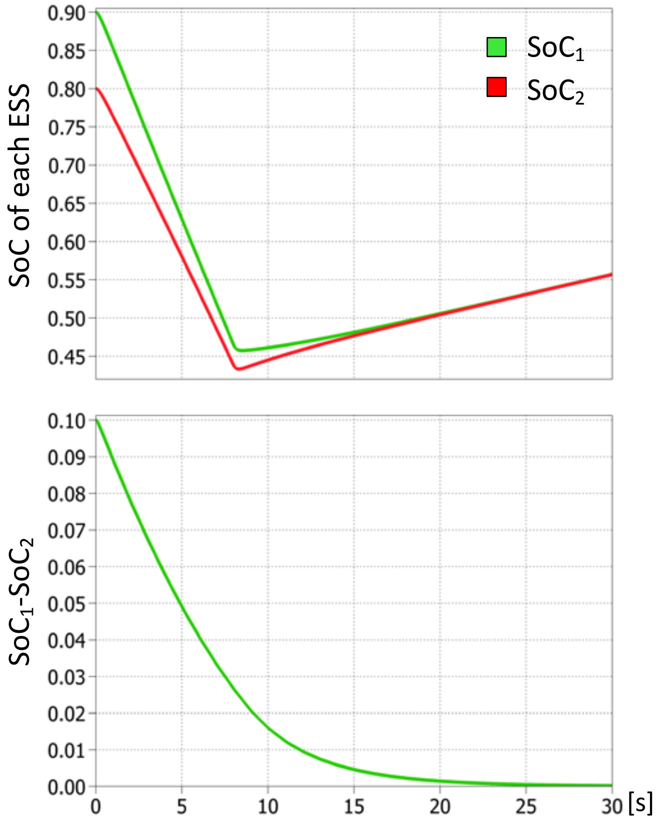


Fig. 7. SoC1, SoC2 and their difference

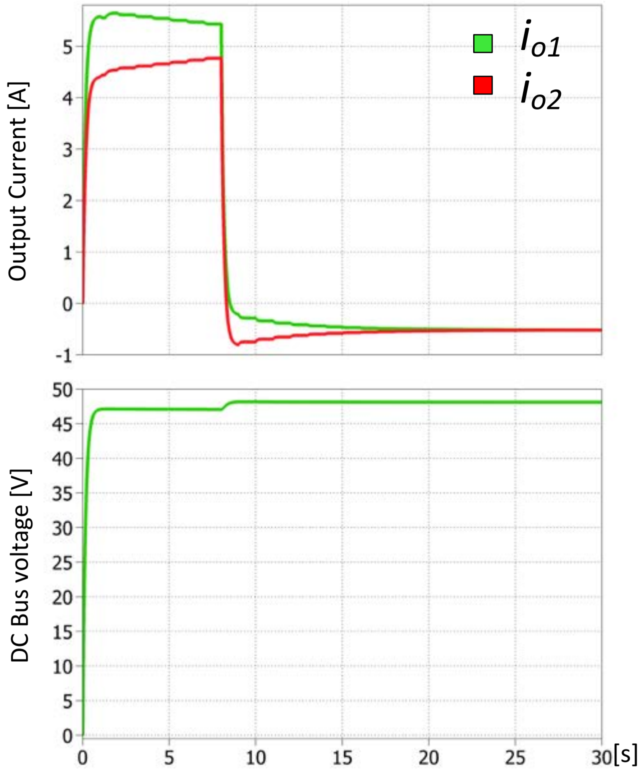


Fig. 8. Output current and DC bus voltage

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